

# GRB 110721A: PHOTOSPHERE “DEATH LINE” AND THE PHYSICAL ORIGIN OF THE GRB “BAND” FUNCTION

BING ZHANG<sup>1,2</sup>, RUI-JING LU<sup>1</sup>, EN-WEI LIANG<sup>1</sup>, XUE-FENG WU<sup>3</sup>

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## ABSTRACT

The prompt emission spectra of gamma-ray bursts (GRBs) usually have a dominant component that is well described by a phenomenological “Band” function. The physical origin of this spectral component is debated. Although the traditional interpretation is synchrotron radiation of non-thermal electrons accelerated in internal shocks or magnetic dissipation regions, a growing trend in the community is to interpret this component as modified thermal emission from a dissipative photosphere of a GRB fireball. We analyze the time dependent spectrum of GRB 110721A detected by *Fermi* GBM and LAT, and pay special attention to the rapid evolution of the peak energy  $E_p$ . We define a “death line” of thermally-dominated dissipative photospheric emission in the  $E_p - L$  plane, and show that  $E_p$  of GRB 110721A at the earliest epoch has a very high  $E_p \sim 15$  MeV that is beyond the “death line”. Together with the finding that an additional “shoulder” component exists in this burst that is consistent with a photospheric origin, we suggest that at least for some bursts, the “Band” component is not from a dissipative photosphere, but must invoke a non-thermal origin (e.g. synchrotron or inverse Compton) in the optically thin region of a GRB outflow. We also suggest that the rapid “hard-to-soft” spectral evolution is consistent with the quick discharge of magnetic energy in a magnetically-dominated outflow in the optically thin region.

*Subject headings:* gamma rays:bursts—gamma rays: observations—gamma rays: theory—plasmas—radiation mechanism: non-thermal— radiation mechanism: thermal

## 1. INTRODUCTION

The prompt emission spectrum of a gamma-ray burst (GRB) is usually well described by a phenomenological function known as the “Band” function (Band et al. 1993). This model, which is essentially a broken power law function with a smooth (exponential) transition, was traditionally invoked to model spectra of GRBs detected by BATSE on board the Compton Gamma-Ray Observatory. The function is found successful to describe most GRB spectra detected by later missions as long as the spectral band is wide enough (e.g. Abdo et al. 2009; Zhang et al. 2011).

The physical origin of this phenomenological Band function is not identified. The traditional model is synchrotron emission of non-thermal electrons in an optically thin region, e.g. internal shocks or internal magnetic dissipation regions (Mészáros et al. 1994; Tavani 1996; Daigne & Mochkovitch 1998; Lloyd & Petrosian 2000; Bosnjak et al. 2009; Zhang & Yan 2011). Alternatively, a matter-dominated outflow (fireball) can have a bright photosphere (Paczynski 1986; Goodman 1986; Mészáros & Rees 2000; Mészáros et al. 2002), which may be enhanced by kinetic or magnetic dissipation processes near the photosphere (Thompson 1994; Rees & Mészáros 2005; Pe’er et al. 2006; Giannios 2008; Beloborodov 2010; Lazzati & Begelman 2010; Ioka 2010). It has been argued that due to geometrical and/or physical broadening, this quasi-thermal component may be mod-

ified to mimic a Band function (e.g. Beloborodov 2010; Lazzati & Begelman 2010; Pe’er & Ryde 2011; Lundman et al. 2012). The scalings of a non-dissipative photosphere model are argued to be able to interpret various empirical correlations (Fan et al. 2012).

Within the framework of the standard fireball-shock model, a GRB prompt emission spectrum is expected to be the superposition of a quasi-thermal photosphere emission component and a non-thermal component in the optically-thin internal shock region (Mészáros & Rees 2000; Zhang & Mészáros 2002; Toma et al. 2011; Pe’er et al. 2012). Such a superposition effect has been claimed in the BATSE data archive (e.g. Ryde 2005; Ryde & Pe’er 2009), and was confirmed more robustly recently with the *Fermi* data (e.g. Ryde et al. 2010; Zhang et al. 2011; Guiriec et al. 2011; Axelsson et al. 2012). On the other hand, most GRB spectra (e.g. GRB 080916C) are still well described by one single Band component (Abdo et al. 2009; Zhang et al. 2011). This sharpens the debate regarding the origin of the Band function. For GRB 080916C, the non-detection of a thermal component led to the suggestion of a Poynting-flux-dominated outflow (Zhang & Pe’er 2009; see also Daigne & Mochkovitch 2002; Zhang & Mészáros 2002). Alternatively, some authors attempted to interpret the entire Band function as emission from a dissipative photosphere (e.g. Beloborodov 2010; Vurm et al. 2011; Giannios 2008; Ioka 2010). These two interpretations invoke distinct assumptions regarding the composition of the GRB jets. Finding observational clues to differentiate between them is therefore essential to unveil the physics of GRB central engine, jet composition and energy dissipation mechanisms, which are poorly constrained (e.g. Zhang 2011).

Here we show that the time-resolved spectral information of GRB 110721A holds the key to address this open

<sup>1</sup> Department of Physics and GXU-NAOC Center for Astrophysics and Space Sciences, Guangxi University, Nanning 530004, China

<sup>2</sup> On leave from Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA

<sup>3</sup> Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China

question.

## 2. “DEATH LINE” OF GRB BARYONIC PHOTOSPHERE EMISSION IN THE $E_p - L$ PLANE

For a hot fireball with total wind luminosity  $L_w$  launched from an initial fireball radius  $R_0$ , the initial temperature is

$$T_0 \simeq (L_w/4\pi R_0^2 c a)^{1/4} \simeq 1.4 \times 10^{10} \text{ K } L_{w,52}^{1/4} R_{0,7}^{-1/2}, \quad (1)$$

where  $c$  is speed of light, and  $a = 7.56 \times 10^{-15} \text{ erg cm}^{-3} \text{ K}^{-4}$  is the Stefan-Boltzmann energy density constant. The observed photosphere temperature  $T_{ph}$  can be as high as  $T_0$  if the fireball is clean enough so that the photosphere radius  $R_{ph}$  does not exceed the fireball coasting radius  $R_c$ , but is lower than  $T_0$  for fireballs with a heavier baryon loading when  $R_{ph} > R_c$ . More specifically, one has (Mészáros & Rees 2000)

$$\frac{T_{ph}}{T_0} = \begin{cases} \left(\frac{R_{ph}}{R_c}\right)^{-2/3} = \left(\frac{\eta}{\eta_*}\right)^{8/3}, & \eta < \eta_*, R_{ph} > R_c, \\ 1, & \eta > \eta_*, R_{ph} < R_c, \end{cases} \quad (2)$$

where  $\eta = L_w/\dot{M}c^2$  is the dimensionless entropy of the fireball, and

$$\eta_* = \left(\frac{L_w \sigma_T}{4\pi m_p c^3 R_0}\right)^{1/4} \simeq 1.04 \times 10^3 \left(\frac{L_{w,52}}{R_{0,7}}\right)^{1/4} \quad (3)$$

is the critical value of  $\eta$ . The photosphere luminosity is  $L_{ph} \simeq \pi(1/\Gamma)^2 R^2 \sigma T^4 \propto (R/\Gamma)^2 T^4 \propto R^2 \Gamma^2 T'^4$ . For  $\eta > \eta_*$ , since  $\Gamma \propto R$  and  $T' \propto R^{-1}$ , one has  $L_{ph} \propto R^0 \sim \text{const.}$  For  $\eta < \eta_*$ , since  $\Gamma \propto R^0$ ,  $T \propto R^{-2/3}$ ,  $L_{ph} \propto R^2 R^{-8/3} \propto R^{-2/3}$ . So the photosphere luminosity is

$$\frac{L_{ph}}{L_w} = \begin{cases} \left(\frac{R_{ph}}{R_c}\right)^{-2/3} = \left(\frac{\eta}{\eta_*}\right)^{8/3}, & \eta < \eta_*, R_{ph} > R_c, \\ 1, & \eta > \eta_*, R_{ph} < R_c, \end{cases} \quad (4)$$

If a GRB spectrum is dominated by the photosphere emission, for a certain observed isotropic  $\gamma$ -ray luminosity  $L = L_{ph}$ , the spectral peak energy  $E_p$  should not exceed  $\zeta k T_0$ , where  $\zeta$  is a factor to denote the  $\nu F_\nu$  peak of the photosphere spectrum. Therefore a baryonic photosphere emission has a “death line” defined by

$$E_p \leq \zeta k T_0 \simeq 1.2 \text{ MeV } \zeta L_{52}^{1/4} R_{0,7}^{-1/2}. \quad (5)$$

The factor  $\zeta$  is subject to the shape of the spectrum. For a strict blackbody,  $\zeta \sim 3.92$ . For a relativistic outflow, the shape of blackbody is modified to the form (see also Li & Sari 2008 and references therein)

$$F_\nu \propto \frac{\nu^2}{c^2} k T \int_{h\nu/kT}^{\infty} \frac{dx}{e^x - 1}. \quad (6)$$

The  $\nu F_\nu$  spectrum has a maximum value at

$$\zeta \sim 2.82. \quad (7)$$

The death line (5) is derived for a non-dissipative photosphere. For a thermally-dominated jet, dissipation via internal shocks or neutron collisional heating near the photosphere would compensate adiabatic cooling, so that the photosphere temperature would be maintained

close to but never exceed the maximum temperature (Beloborodov 2012), so eq.(5) applies to a broad categories of dissipative photosphere models as well. A possible exception would be the dissipative photosphere model that invokes continued magnetic dissipation at extended radii above the photosphere (Drenkhahn & Spruit 2002), which allows  $E_p$  to be above the death line (5) if the bulk Lorentz factor is large enough and dissipation at high optical depth is suppressed (Giannios 2012). However, in order to thermalize the jet, the required Lorentz factor is very low (Vurm et al. 2012), making it essentially impossible to exceed the death line. Also this model may not interpret the GRB 110721A phenomenology, including the existence of the shoulder thermal component and the rapid spectral softening during the rising phase of bolometric luminosity (see Sect. 3).

## 3. GRB 110721A

GRB 110721A was jointly detected by the Gamma-Ray Burst Monitor (GBM; Meegan et al. 2009) and the Large Area Telescope (LAT; Atwood et al. 2009) onboard the Fermi Gamma-Ray Telescope (Axelsson et al. 2012 and references therein). A candidate optical counterpart was reported (Greiner et al. 2012). Assuming that the association is real, Berger (2012) suggested two possible redshifts  $z = 0.382$  or  $z = 3.512$ , with the former one preferred.

The time-dependent spectral evolution of GRB 110721A was reported by Axelsson et al. (2012). Two noticeable features of the burst are: 1. A thermal component is identified to be superposed on the Band component in both the time integrated spectrum and time-resolved spectra. The temperature of this “shoulder” thermal component evolves with time as a broken power law, which is consistent with the expectations of the photosphere model (Ryde & Pe’er 2009). 2. The Band component displays an extremely rapid spectral evolution. The  $E_p$  at the earliest epoch reaches a record-breaking value  $\sim 15 \text{ MeV}$ .

We have independently processed the Fermi data of GRB 110721A. We performed a joint spectral analysis using the data from the NaI 6, 7 and BGO 1 detectors on GBM, as well as the LAT data<sup>4</sup>. For GBM, we used the TTE event data containing individual photons with time and energy tags. Background rates are estimated by fitting the light curve before and after the burst using a one-order background polynomial model. We pretreated the LAT data using the LAT ScienceTools-v9r27p1 package and the P7TRANSIENT\_V6 response function (detailed informatin for the LAT GRB Analysis are available in the NASA *Fermi* web site<sup>5</sup>). In the diffuse response calculation, a three-component model is used: GRB 100721A with a PowerLaw2 spectrum, the Galactic diffuse model of gal2yearp7v6\_v0.fits, and the extragalactic diffuse power law model. We then extracted the background-subtracted light curves from the GBM and LAT and demonstrated them in Figure 1. It is obvious that higher energy photons arrive earlier than the lower energy photons.

<sup>4</sup>

<http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>

<sup>5</sup>

<http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/lat-grb-analysis.html>

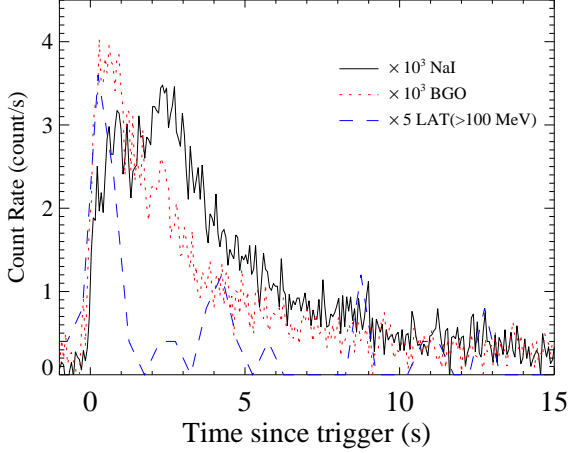


FIG. 1.— The light curves of GRB 110721A in different energy bands: solid: NaI; short dash: BGO; long dash: LAT above 100 MeV.

In order to better understand the cause of such a behavior, we carry out a detailed time-dependent spectral analysis. We adjust the size of the time bins so that each time bin contains enough photons to perform a statistically significant spectral analysis. We applied the software package RMFIT (version 3.3pr7) to carry out the analyses. We confirm the conclusion of Axelsson et al. (2012) that adding a shoulder thermal component can improve the fits to the data significantly. Since the evolution of the thermal component has been presented in Axelsson et al. (2012), in this paper we focus on the Band component only in order to study its physical origin. We find that the Band model usually gives a reasonable fit to the data, with the reduced  $\chi^2$  in the range  $\sim (0.9 - 1.1)$ . Figure 2 gives an example of the Band model fitting the data in the time interval of  $[-0.512, 0.064]$ s. This earliest epoch indeed shows an extremely high  $E_p$  value  $\sim 19.6 \pm 4.5$  MeV, which is consistent with  $E_p = 15 \pm 1.7$  MeV reported by Axelsson et al. (2012). The larger error in our fit may be because the Fermi team has included the extra LLE (LAT Low Energy) data, which is currently unavailable to the public. We also present the best fit  $\nu F_\nu$  model curves in different time intervals in Fig.3.

Figure 4 displays the rest-frame  $E_p - L$  plot for time-resolved spectra of Fermi GRBs with well measured redshifts. The data are a sub-sample of Fig.9 of Lu et al. (2012), for which only the parameters during the rising phase of GRB pulses are adopted. This is because the decaying phase may be controlled by the high-latitude curvature effect, which does not directly reveal radiation physics. Two “death lines” (eq.[5]) are drawn, which correspond to  $R_0 \sim 10^7$  cm (solid, typical value) and  $R_0 \sim 3 \times 10^6$  cm (dashed, an extreme value to allow highest death line possible). GRB 110721A at the earliest epoch  $[-0.512, 0.064]$ s is plotted for two candidate redshifts. It is clearly seen from the figure that for both redshifts, the points are way above the death lines. This rules out a wide range of dissipative photosphere models at least for this earliest epoch.

One may make one step further. Axelsson et al. (2012) showed that  $E_p$  evolution of the Band component can be fit as a power-law decay with time, suggesting that this component might have a same physical origin during the

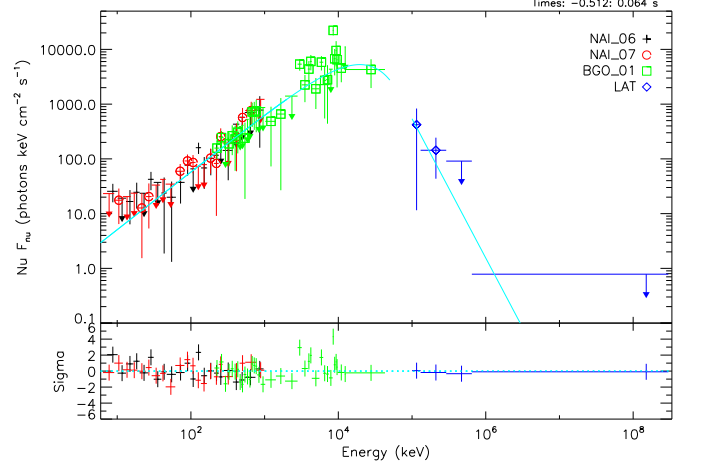


FIG. 2.— Data and Band function model curve of GRB 110721A in the time interval of  $[-0.512, 0.064]$ s. The solid line is the best Band function fit with parameters  $\alpha = -0.944 \pm 0.046$ ,  $\beta = -4.543 \pm 0.887$ , and peak energy  $E_p = (1.956 \pm 0.422) \times 10^4$  keV, which are consistent with Axelsson et al. (2012).

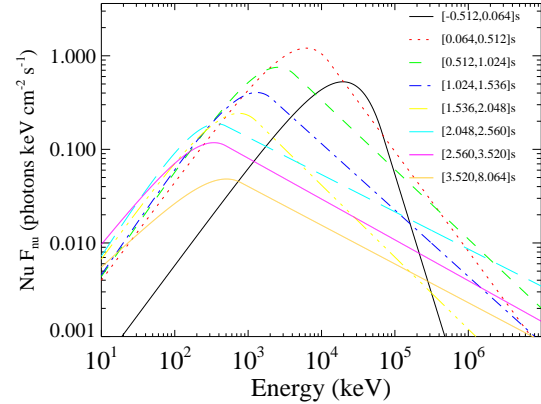


FIG. 3.— The best-fit  $\nu F_\nu$  model spectra for the time resolved data in different time bins (as marked in the legend).

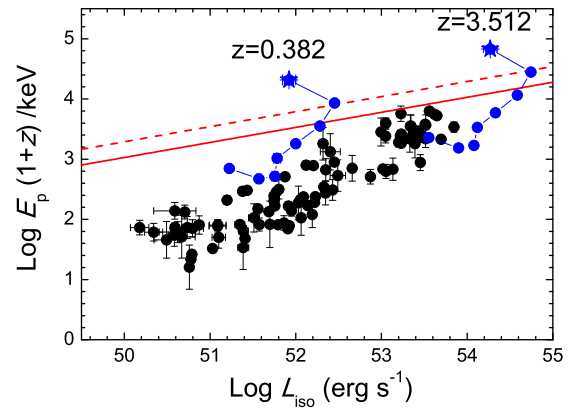


FIG. 4.— The rest-frame peak energy  $E_p(1+z)$  is plotted against the observed isotropic  $\gamma$ -ray luminosity  $L$  for the time resolved spectra of Fermi GRBs with redshift measurements. The black data points are from Fig. 9 of Lu et al. (2012), but only the spectra during the rising phase of GRB pulses are taken (see text for explanation). The blue points are the time-resolved spectra of GRB 110721A for the two candidate redshifts. The two stars are for the first epoch, which are both well beyond the death lines. Two death lines are plotted, which correspond to  $R_0 = 10^7$  cm (solid) and  $3 \times 10^6$  cm (dashed), respectively.

burst. Figure 3 displays evolution of the spectral shape of the Band component, which shows a similar  $\alpha$  value with a gradually shallowing  $\beta$  value. This suggests that the Band component should share the same physical origin in different epochs: it is not from the photosphere, but is likely from an optically thin region where non-thermal particles are accelerated.

#### 4. SUMMARY AND DISCUSSION

We have shown that the Band function component of GRB 110721A is beyond the “death line” of thermally-dominated dissipative photosphere models in the  $E_p - L$  plane. Together with the fact that an additional shoulder thermal component is consistent with the photosphere model, we reach the conclusion that the so-called “Band” component is *not* of a photospheric origin at least for this burst, and is formed via non-thermal dissipation processes in the optically thin regions. Veres et al. (2012) interpreted this emission as synchrotron emission from a magnetically-dominated jet.

Such a finding has profound implications in understanding the origin of other Band function spectra of GRBs. Zhang et al. (2011) identified three elemental spectral components through a detailed time-resolved spectral analysis of 17 GRBs co-detected with Fermi GBM and LAT. They found that there are two types of GRBs. GRB 080916C’s spectra remain the “Band” shape even though the time interval for the spectral analysis progressively reduces, reaching  $\sim 1$  s in the rest frame. GRB 090902B, on the other hand, showed a clear “narrowing” feature as time bin reduces, and spectrum is much narrower at  $\sim$  rest-frame 1 s. The time integrated spectrum of this burst is also narrower than other Band GRBs. This burst’s “Band” component can be indeed de-composed as superposed photosphere emission (Ryde et al. 2010; Zhang et al. 2011; Pe’er et al. 2012; Mizuta et al. 2011). However, such bursts are not common. Most bursts are similar to GRB 080916C.

The spectral parameters of GRB 110721A are similar to those of GRB 080916C and many other GRBs. The conclusion that the Band component of GRB 110721A originates from the optically thin region also supports the suggestion that most Band components are non-thermal (synchrotron or SSC) emission in the optically thin region. Available data seem to suggest the following unified picture: The GRB central engine may have a range of magnetization parameter  $\sigma_0$ . 1. For low  $\sigma_0$  bursts, dissipation can occur at small radii, so that a bright photospheric emission component (such as the case of

GRB 090902B) is detected. Such bursts are usually accompanied by a high energy component due to upscattering of the thermal photons (and probably also synchrotron self-Compton, Pe’er et al. 2012). 2. For intermediate  $\sigma_0$  bursts, the photosphere component is weaker but still detectable. Examples of this category include GRB 110721A (Axelsson et al. 2012) and GRB 100724B (Guiriec et al. 2011). The Band component of these bursts are formed in the large radii via internal shocks (IS) or internal collision-induced magnetic reconnection and turbulence (ICMART). 3. Finally, if  $\sigma_0$  is large enough, both the photosphere and IS components are suppressed. The Band component forms at even larger radii via the ICMART process (Zhang & Yan 2011).

Finally, very rapid hard-to-soft  $E_p$  evolution observed in GRB 110721A (Axelsson et al. 2012 and this work) and many other GRBs (Lu et al. 2010, 2012) challenges existing models. Such a rapid evolution is not expected in the internal shock model. For the photosphere model, some moderate hard-to-soft evolution may be expected due to the initial growth of optical depth in a fireball (W. Deng & B. Zhang 2012, in preparation), but never an extreme evolution like GRB 110721A. A possible interpretation may be made within the framework of the ICMART model. According to this model (Zhang & Yan 2011),  $\sigma$  in the emission region rapidly decreases during each ICMART event, since the magnetic energy is continuously dissipated. If a good fraction of local magnetic dissipation energy is deposited to electrons, the typical electron Lorentz factor  $\gamma_e$  would have a  $\sigma$ -dependence, so that  $E_p$  decreases with time as  $\sigma$  reduces. Also relativistic turbulent reconnection would lead to locally Doppler-boosted mini-jets, whose Lorentz factors would also depend on the local  $\sigma$  value (Zhang & Zhang 2012). The time dependent Doppler boosts for mini-jets would enhance the hard-to-soft  $E_p$  evolution.

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#### REFERENCES

- Abdo, A.A., et al. 2009, *Science*, 323, 1688  
 Atwood, W. B. et al. 2009, *ApJ*, 697, 1071  
 Axelsson, M. et al. 2012, *ApJ*, submitted (arXiv:1207.6109)  
 Band, D. et al. 1993, *ApJ*, 413, 281  
 Beloborodov, A. 2010, *MNRAS*, 407, 1033  
 Beloborodov, A. 2012, *ApJ*, submitted (arXiv:1207.2707)  
 Berger, E. 2011, *GCN Circ.* 12193  
 Bosnjak, Z., Daigne, F., Dubus, G. 2009, *A&A*, 498, 677  
 Daigne, F., & Mochkovitch, R. 1998, *MNRAS*, 296, 275  
 Daigne, F., & Mochkovitch, R. 2002, *MNRAS*, 336, 1271  
 Drenkhahn, G., & Spruit, H. C. 2002, *A&A*, 391, 1141  
 Fan, Y.-Z., Wei, D.-M., Zhang, F.-W., Zhang, B.-B. 2012, *ApJ*, 755, L6  
 Giannios, D. 2008, *A&A*, 480, 305  
 Giannios, D. 2012, *MNRAS*, 422, 3092  
 Goodman, J. 1986, *ApJ*, 308, L47  
 Greiner, J. et al. 2011, *GCN Circ.* 12192  
 Guiriec, S. et al. 2011, *ApJ*, 727, L33  
 Ioka, K. 2010, *Prog. Theo. Phys.* 124, 667  
 Lazzati, D. & Begelman, M. C. 2010, *ApJ*, 725, 1137  
 Li, C. & Sari, R. 2008, *ApJ*, 677, 425  
 Lloyd, N. M. & Petrosian, V. 2000, *ApJ*, 543, 722  
 Lu, R.-J., Hou, S.-J., Liang, E.-W. 2010, *ApJ*, 720, 1146  
 Lu, R.-J. et al. 2012, *ApJ*, in press (arXiv:1204.0714)  
 Lundman, C., Pe’er, A., Ryde, F. 2012, *MNRAS*, submitted (arXiv:1208.2965)

- Meegan, C. et al. 2009, ApJ, 702, 791  
Mészáros, P., Rees, M. J., Papathanassiou, H. 1994, ApJ, 432, 181  
Mészáros, P., & Rees, M.J. 2000, ApJ, 530, 292  
Mészáros, P., Ramirez-Ruiz, E., Rees, M.J., & Zhang, B. 2002, ApJ, 578, 812  
Mizuta, A., Nagataki, S., Aoi, J. 2011, ApJ, 732, 26  
Paczynski, B. 1986, ApJ, 308, L43  
Pe'er, A., Mészáros, P., & Rees, M.J. 2006, ApJ, 642, 995  
Pe'er, A., & Ryde, F. 2011, ApJ, 732, 49  
Pe'er, A. et al. 2012, MNRAS, 420, 468  
Rees, M.J., & Mészáros, P. 2005, ApJ, 628, 847  
Ryde, F. 2005, ApJ, 625, L95  
Ryde, F., & Pe'er, A. 2009, ApJ, 702, 1211  
Ryde, F. et al. 2010, ApJ, 709, L172  
Tavani, M. 1996, ApJ, 466, 768  
Thompson, C. 1994, MNRAS, 270, 480  
Toma, K., Wu, X.-F., Mészáros, P. 2011, MNRAS, 415, 1663  
Veres, P., Zhang, B.-B., Mészáros, P. 2012, ApJ, submitted (arXiv:1208.1709)  
Vurm, I., Beloborodov, A. M., Poutanen, J. 2011, ApJ, 738, 77  
Vurm, I., Lyubarsky, Y., Piran, T. 2012, ApJ, submitted (arXiv:1209.0763)  
Zhang, B. 2011, Comptes Rendus Physique, 12, 206  
Zhang, B. & Mészáros, P. 2002, ApJ, 581, 1236  
Zhang, B. & Pe'er, A. 2009, ApJ, 700, L65  
Zhang, B. & Yan, H. 2011, ApJ, 726, 90  
Zhang, B. & Zhang, B. 2012, MNRAS, submitted  
Zhang, B.-B. et al. 2011, ApJ, 730, 141